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THE PROTECTION OF FRONT SURFACED ALUMINIUM MIRRORS WITH DIAMOND--ETC(U)
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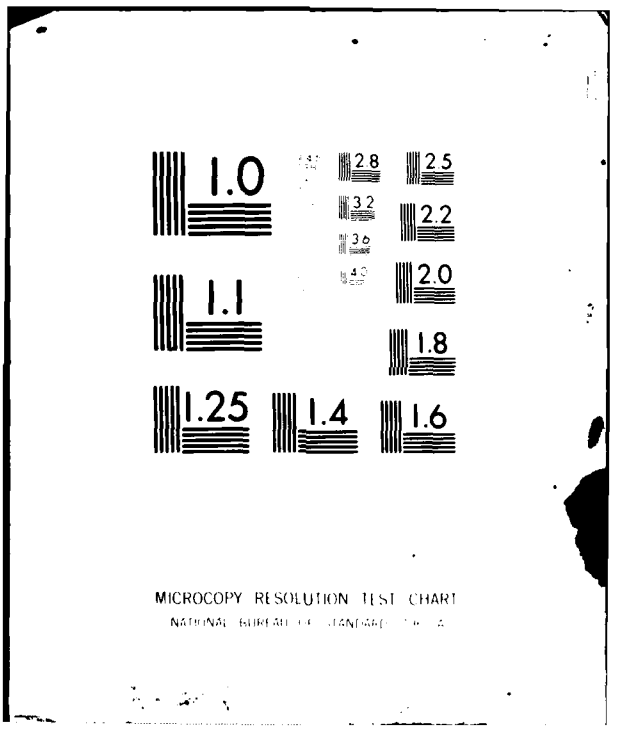
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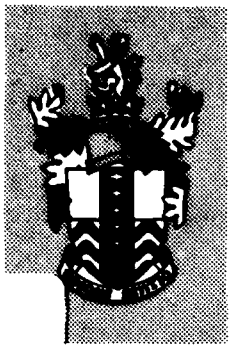

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THE PROTECTION OF FRONT SURFACED ALUMINIUM MIRRORS WITH DIAMOND-LIKE CARBON COATINGS FOR USE IN THE INFRARED

Authors: A H Lettington
and G J Ball

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Memorandum 3295

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Authors: (10) A H Lettington ~~and~~ G J Ball

Date: (11) January 1981

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SUMMARY

It has recently been shown that aluminium mirrors protected with a variety of thin passivation layers have severe reflectivity losses in the 8-12 μm spectral region when used at oblique incidence. This memorandum presents measurements and calculations illustrating this effect and derives the condition that the loss will occur if $\cos\phi < (n_1^2 + k_1^2)^{-\frac{1}{2}}$ where ϕ is the angle of incidence. Its main purpose is to propose the use of an infrared transmitting diamond-like carbon coating for metallic reflectors in this 8-12 μm band. These coatings, in addition to being abrasion resistant and chemically durable, do not exhibit a reflectivity loss at angles of incidence of practical importance.

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THE PROTECTION OF FRONT SURFACED ALUMINIUM MIRRORS WITH DIAMOND-LIKE CARBON COATINGS FOR USE IN THE INFRARED

A H Lettington and G J Ball

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1 INTRODUCTION

It has been demonstrated recently[1],[2] that aluminium mirrors protected with thin overcoatings of SiO, SiO_2 or a mixture of the two have severe reflectivity losses in the 8-12 μm spectral band when used at non-normal incidence, particularly so when the angle of incidence is greater than 40 degrees.

This effect occurs for only one direction of polarisation R_p, parallel to the plane of incidence, and is not observed at normal incidence nor in uncoated aluminium at oblique incidence.

The oxides of silicon are the most commonly used overcoatings for fresh aluminium mirrors and - although they prevent the mirrors tarnishing, are durable and provide protection against humidity and abrasion - they are totally unsuitable for use in 8-12 μm thermal imaging systems as protective coatings for 45 degree mirrors or scanning reflecting polygons.

Similarly, effects are observed for many other protective coatings and for other metallic reflectors[2],[3]. As an example we illustrate in figures 1 and 2 the experimental reflectivities of commercially available protected aluminium and silver measured for us at two angles of incidence, normal incidence and 45 degrees, by SIRA institute[9].

Previous authors have discussed with varying degrees of success the ranges of n and k for which this reflectivity dip might occur[1],[3],[4]. In this paper we outline the mechanism responsible for this effect and discuss the conditions under which this loss in reflectivity occurs. We also propose the use of a diamond-like carbon coating as a protective layer for front surfaced mirrors. From our measured values of n and k we conclude that such a carbon coating will not exhibit a reflectivity loss at oblique angles of incidence.

2 MECHANISM FOR REFLECTIVITY LOSS

The reflectivity of the dielectric metal structure may be computed[5] from known values of n and k for both the metal and dielectric. We have used those values tabulated by Cox et al in Ref 1 for aluminium, SiO and SiO_2 in the 8-12 μm region (the original references being (6), (7) and (8) respectively), and have computed the normal incidence reflectivity and R_S and R_P components at 45 degree and 60 degree angles of incidence for both bare aluminium and for aluminium overcoated with 1500 Å thicknesses of SiO or SiO_2. The results, which are identical to the previous calculations of Cox et al[1], are reproduced in table 1 for comparison purposes. These results for the 45 degree angle of incidence are also included in figure 1.

We have studied analytically the phase and amplitude relationships for light waves at the air-dielectric and dielectric-metal interfaces and have concluded that the reflectivity loss occurs when there is destructive interference between the reflected components from the air-dielectric and dielectric-metal interfaces. For metals with high reflectivities in the infrared the values of n and k are such that there is always a phase change of approximately π on reflection at the dielectric-metal boundary for all angles of incidence of practical importance. At the air-dielectric interface however there is a phase change of between π and π/2 on reflection at normal incidence and for increasing angles of incidence until the principal angle is reached, beyond which the phase change is between π/2 and zero. The thickness of the coatings is generally so small that the path difference and absorption within the layer are negligible. This is true even when there is a strong absorption peak within the dielectric. However the presence of the absorption peak strongly affects the values of n and k for the dielectric and dramatically influences the value of the principal angle at the air-dielectric boundary so that it occurs at quite modest angles of incidence giving rise to the reflectivity loss.

The condition for the principal angle derived from the Fresnel coefficient is given by:

$$\left(n_1^2 + k_1^2\right)^2 \cos^2 \phi_P = \left[\left(n_1^2 - k_1^2 - \sin^2 \phi_P\right)^2 + 4n_1^2 k_1^2\right]^{\frac{1}{2}} \quad (1)$$

Where n_1, k_1 and ϕ_P are the refractive index, extinction coefficient and principal angle respectively. This may be approximated and rewritten such that destructive interference occurs whenever the following inequality is satisfied:

$$\cos \phi < \left(n_1^2 + k_1^2\right)^{-\frac{1}{2}} \quad (2)$$

where ϕ is the angle of incidence.

If in eqn (2) ϕ is set to 45 degrees then from the tabulated values of n and k for SiO and SiO_2 given in table one we find that the inequality is satisfied over the wavelength range 8.0 to 9.2 μm for SiO and 8.0 to 8.8 μm for SiO_2 which may be compared with the positions of the reflectivity minima in fig 1. Agreement between the position of the reflectivity dips and the spectral regions predicted from eqn (2) is excellent for both the calculated spectra and also for the experimental curve for commercially protected aluminium, which is probably a mixture of the two oxides.

3 OPTICAL PROPERTIES OF CARBON COATINGS ON METALLIC REFLECTORS

Within our laboratory techniques have been developed[10] to deposit infrared transmitting, abrasion resistant, chemically durable carbon coatings on a variety of metals and dielectrics. Values of n and k for the carbon layers were calculated from transmission and reflection measurements between 2 and 14 μm for layers deposited on glass and germanium substrates. The refractive index n was found to have a value of 2.2 to within experimental error over the specified range of interest. The values of k depended to some extent on the deposition conditions and the nature of the substrate. The values used in the following calculations are given in table two.

From our derived values of n and k for carbon and the previously mentioned values for aluminium we have comptued the infrared reflectivity of aluminium mirrors overcoated with 5000 Å and 1500 Å thicknesses of carbon. The results are given in table two for comparison with the results for SiO and SiO_2 layers

in table one. It is seen that the reflectivities are not significantly reduced at angles of incidence of 45 degrees and 60 degrees for the carbon coating. This is what we would anticipate from the discussion in section 2 since in carbon there is no strong absorption peak in the infrared to reduce the principal angle to values of practical significance.

From the results presented in table two we conclude that a thickness of carbon of 1500 Å would be suitable for both the 3-5 μm and 8-12 μm regions of the spectrum, although for use in the 3-5 μm region alone the more conventional SiO coating may be more appropriate.

In conclusion we believe that carbon overcoating of metallic reflectors is optically very efficient and is probably the most cost effective method for producing an abrasion resistant, chemically durable, protected surface. With mirrors protected in this way applications such as catadioptric telescopes permanently exposed to the atmosphere can be envisaged.

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TABLE ONE. OPTICAL CONSTANTS OF AL, SiO AND SiO_2 AND REFLECTIVITIES OF AL AND AL-SiO, AL-SiO_2 SYSTEMS

WAVELENGTH (μm)	AL		AL 0°	AL 45°			AL 60°			SiO		Al + SiO (t = 1500Å) 0°	Al + SiO (t = 1500Å) 45°			Al + SiO (t = 1500Å) 60°			SiO_2		AL + SiO_2 (t = 1500Å) 0°	AL + SiO_2 (t = 1500Å) 45°			AL + SiO_2 (t = 1500Å) 60°		
	n	k	R	R_S	R_P	R	R_S	R_P	R	n	k	R	R_S	R_P	R	R_S	R_P	R	n	k	R	R_S	R_P	R	R_S	R_P	R
8.0	17.9	55.3	97.9	98.5	97.1	97.8	99.0	95.9	97.5	1.15	0	97.9	98.5	97.0	97.8	98.9	95.9	97.4	0.35	<0.1	97.9	98.5	97.6	98.1	99.0	98.2	98.6
8.2	18.8	56.2	97.9	98.5	97.2	97.9	98.9	95.8	97.4	1.04	0	97.9	98.5	97.0	97.8	98.9	95.8	97.4	0.43	0.58	97.8	98.4	54.9	79.7	98.9	30.7	73.2
8.4	19.5	57.5	97.9	98.5	97.1	97.8	99.0	95.9	97.5	0.95	0.13	97.8	98.5	88.5	93.6	98.9	78.8	89.4	0.50	0.90	97.7	98.4	76.0	87.9	98.9	59.1	81.5
8.6	20.3	58.8	97.9	98.5	97.0	97.8	99.0	95.9	97.5	0.87	0.31	97.8	98.4	77.2	88.4	98.9	58.9	81.4	0.48	1.02	97.7	98.4	81.0	90.1	98.9	67.0	84.5
8.8	21.0	60.0	97.9	98.5	97.1	97.8	99.0	95.9	97.5	0.85	0.51	97.8	98.4	74.2	87.1	98.9	54.4	79.8	0.37	1.30	97.8	98.4	89.2	93.9	98.9	81.1	90.4
9.0	21.8	61.1	98.0	98.6	97.1	97.9	99.0	95.9	97.5	0.90	0.70	97.7	98.4	78.0	88.8	98.8	61.0	82.2	0.90	2.65	97.2	98.0	94.0	96.0	98.6	90.5	94.6
9.2	22.5	62.4	98.0	98.6	97.2	97.9	99.0	96.0	97.5	0.96	0.92	97.6	98.3	82.5	90.7	98.8	68.7	85.1	2.20	3.02	95.6	96.9	92.2	94.6	97.8	88.2	93.1
9.4	23.3	63.7	98.0	98.6	97.2	97.9	99.0	96.0	97.5	1.10	1.15	97.5	98.3	86.6	92.6	98.8	76.1	88.2	3.65	3.00	93.8	95.6	90.4	93.0	96.9	86.3	91.8
9.6	24.0	65.0	98.0	98.6	97.2	97.9	99.0	96.1	97.6	1.30	1.25	97.5	98.2	88.8	93.6	98.7	80.1	89.9	3.73	1.70	95.3	96.7	92.4	94.6	97.6	89.0	93.4
9.8	25.0	66.1	98.0	98.6	97.2	97.9	99.0	96.1	97.6	1.60	1.32	97.3	98.1	90.6	94.4	98.6	83.7	91.5	3.25	0	97.8	98.4	96.9	97.7	98.9	95.8	97.4
10.0	26.0	67.3	98.0	98.6	97.2	97.9	99.0	96.1	97.6	1.90	1.38	97.2	98.0	91.9	95.0	98.6	86.2	92.6	2.90	0	97.8	98.5	97.0	97.8	98.9	95.9	97.4
10.2	26.4	68.2	98.1	98.6	97.3	98.0	99.0	96.1	97.6	2.30	1.33	97.1	97.9	93.0	95.5	98.5	88.4	93.6	2.70	0	97.9	98.5	97.1	97.8	98.9	96.0	97.5
10.5	27.5	70.0	98.1	98.6	97.3	98.0	99.0	96.2	97.6	2.80	0.9	97.2	98.0	94.6	96.3	98.6	91.5	95.1									
11.0	29.3	72.7	98.1	98.6	97.3	98.0	99.0	96.2	97.6	2.80	0.4	97.7	98.4	96.0	97.2	98.8	93.9	96.4									
11.5	31.2	75.3	98.1	98.7	97.4	98.1	99.1	96.3	97.7	2.55	0.23	97.9	98.5	96.5	97.5	99.0	94.7	96.9									
12.0	33.1	78.0	98.2	98.7	97.4	98.1	99.1	96.3	97.7	2.12	0.16	98.1	98.6	96.6	97.6	99.0	94.8	96.9									

TABLE TWO: OPTICAL CONSTANTS OF DIAMONDLIKE CARBON AND REFLECTIVITIES OF AL AND AL-C SYSTEMS

WAVELENGTH (μm)	AL							C		AL + C (t = 1500 Å)							AL + C (t = 5000 Å)						
	0°	45°			60°					0°	45°			60°			0°	45°			60°		
	R	R_S	R_P	R	R_S	R_P	R	n	k	R	R_S	R_P	R	R_S	R_P	R	R	R_S	R_P	R	R_S	R_P	R
3.0	96.8	97.8	95.6	96.7	98.4	93.8	96.1	2.2	0.027	93.9	95.6	92.3	94.0	96.8	91.0	93.9							
3.5	97.0	97.9	95.8	96.9	98.5	94.2	96.4	2.2	0.028	95.1	96.5	93.6	95.1	97.5	92.0	94.8							
4.0	97.5	98.2	96.5	97.4	98.7	95.1	96.9	2.2	0.031	96.3	97.4	94.9	96.2	98.1	93.4	95.8							
4.5	97.4	98.2	96.4	97.3	98.7	94.9	96.8	2.2	0.033	96.5	97.5	95.1	96.3	98.2	93.5	95.9							
5.0	97.5	98.2	96.5	97.4	98.7	95.1	96.9	2.2	0.035	96.3	97.7	95.4	96.6	98.4	93.8	96.1							
8.0								2.2	0.046	97.7	98.4	96.6	97.5	98.8	95.1	97.0	93.1	94.9	91.7	93.3	96.3	90.7	93.5
8.2								2.2	0.046	97.7	98.4	96.6	97.5	98.8	95.1	97.0	93.4	95.2	92.0	93.6	96.5	90.9	93.7
8.4								2.2	0.047	97.7	98.4	96.6	97.5	98.9	95.1	97.0	93.8	95.4	92.3	93.9	96.7	91.1	93.9
8.6								2.2	0.048	97.7	98.4	96.6	97.5	98.9	95.2	97.1	94.1	95.7	92.5	94.1	96.9	91.3	94.1
8.8								2.2	0.049	97.8	98.4	96.6	97.5	98.9	95.2	97.1	94.3	95.9	92.7	94.3	97.0	91.4	94.2
9.0								2.2	0.049	97.8	98.4	96.7	97.6	98.9	95.2	97.1	94.6	96.1	93.0	94.6	97.2	91.6	94.4
9.2								2.2	0.050	97.8	98.4	96.7	97.6	98.9	95.3	97.1	94.8	96.3	93.2	94.8	97.3	91.8	94.6
9.4								2.2	0.051	97.8	98.4	96.7	97.6	98.9	95.3	97.1	94.9	96.3	93.3	94.8	97.4	91.8	94.6
9.6								2.2	0.052	97.9	98.5	96.8	97.7	98.9	95.4	97.2	95.3	96.6	93.6	95.1	97.5	92.1	94.8
9.8								2.2	0.052	97.9	98.5	96.8	97.7	98.9	95.4	97.2	95.4	96.7	93.7	95.2	97.6	92.2	94.9
10.0								2.2	0.053	97.9	98.5	96.8	97.7	98.9	95.4	97.2	95.6	96.8	93.9	95.4	97.7	92.3	95.0
10.5								2.2	0.055	98.0	98.6	96.9	97.8	99.0	95.6	97.3	95.9	97.1	94.3	95.7	97.9	92.7	95.3
11.0								2.2	0.057	98.0	98.6	97.0	97.8	99.0	95.6	97.3	96.2	97.3	94.6	96.0	98.1	92.9	95.5
11.5								2.2	0.059	98.0	98.6	97.0	97.8	99.0	95.7	97.4	96.5	97.5	94.8	96.2	98.2	93.1	95.7
12.0								2.2	0.061	98.1	98.6	97.1	97.9	99.0	95.8	97.4	96.7	97.6	95.0	96.3	98.3	93.4	35.9
13.0								2.2	0.065	98.2	98.7	97.2	98.0	99.1	96.0	97.5	97.1	97.9	95.5	96.7	98.5	93.8	96.2
14.0								2.2	0.068	98.3	98.8	97.3	98.1	99.1	96.2	97.6	97.4	98.1	95.8	97.0	98.7	94.1	96.4

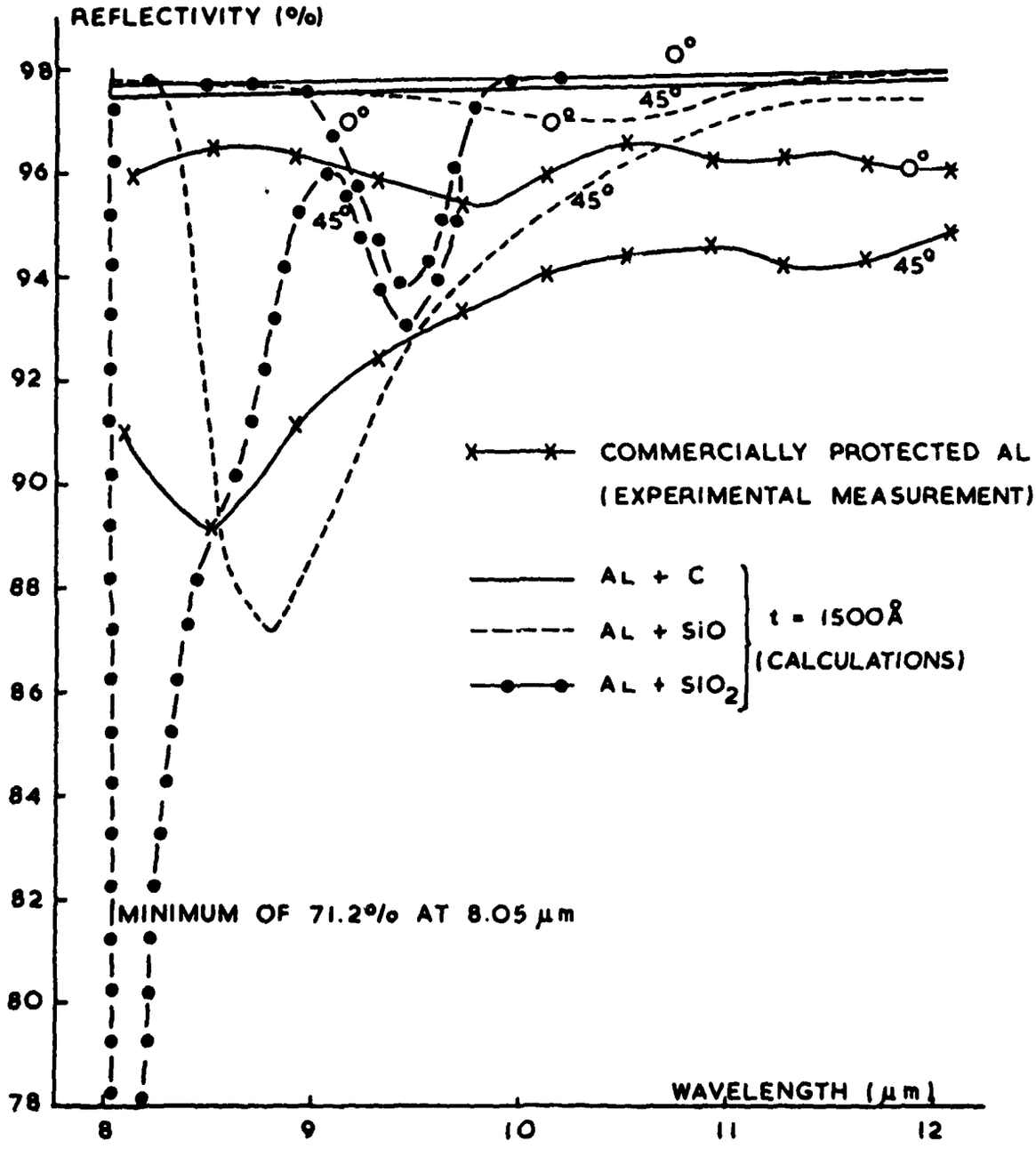

FIG. 1. REFLECTIVITY OF COMMERCIALLY PROTECTED ALUMINIUM AND AL + SiO, AL + SiO_2 AND AL + C

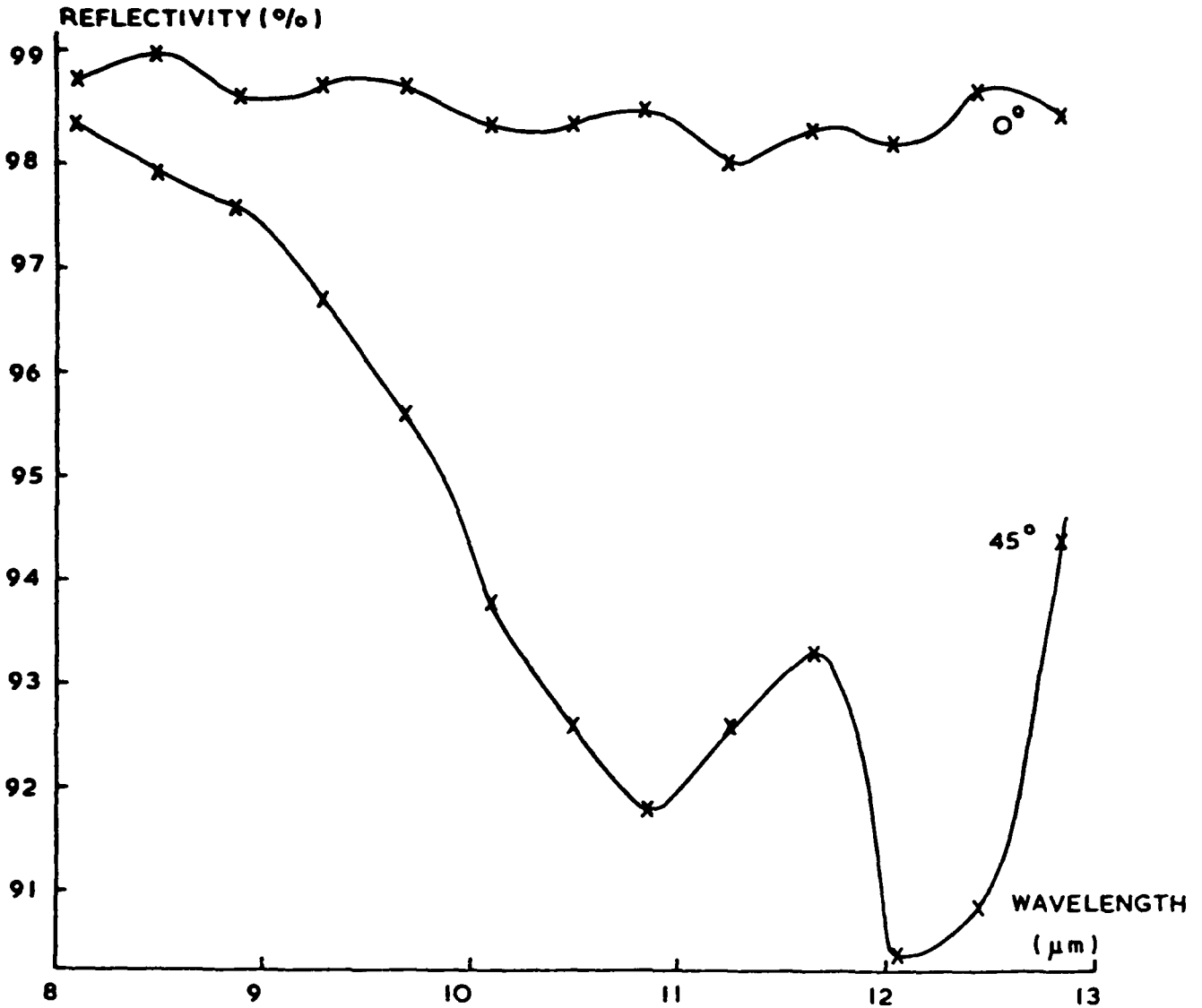

FIG. 2. REFLECTIVITY OF COMMERCIALLY PROTECTED SILVER